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HEAT TRANSFER IN A CONCRETE COMPOSITE CROSS-SECTION

Abstract

The work is concerned with the spread of heat in 2D coupled cross section with respect to the material characteristics and boundary conditions of calculation. Heat transfer was simulated in the program ANSYS in time interval up to 180 minutes. Nine various models were created to investigate the rate of influence of the changes in thermal material characteristics such as the specific heat capacity coefficient and thermal conductivity, upon the course and difference of temperature in the concrete cross-section. The comparison of results obtained using non-linear and constant values of the variables in simulation was made, too.

Keywords

Fire, heat transfer, nonlinear thermal properties, ANSYS.

1 INTRODUCTION

Within the design of structures, the effects of fire must be considered. Thermal and mechanical properties of materials have been changed due to influence of high temperatures. In steel and aluminum constructions effects of higher temperatures are particularly improper. In regard to their high heat conductivity and suability of cross-sections the change of mechanical parameters occurs in relatively short time interval. Warming of massive concrete structures is considerably slower, thus the combination of concrete and steel in coupled cross-sections has many advantages from the viewpoint of the structural fire restistance.

2 THERMAL PROPERTIES OF MATERIALS

The rate of increase of temperatures in steel concrete composite cross-sections depends on thermal properties of materials. These properties are represented by thermal conductivity λ (W/mK), heat conductivity factor α (m^2/s), density ρ (kg/m^3) and specific heat c (J/kgK).

Interdependence between thermal properties can be expressed for example:

$$\alpha = \frac{\lambda}{c.\rho} \quad . \tag{1}$$

Thermal conductivity reflects the ability of materials to conduct heat and its dependence on temperature is as follows:

$$\lambda = \lambda_0 \left(1 \pm A\theta \pm B\theta^2 \pm \ldots\right) . \tag{2}$$

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2.1 Thermal properties of concrete

Concrete is an artificial hygroscopic building material, consisting of a mixture of filler, binder, water, and its properties modifying additive. The major process is a dehydration of the binder phase of CSH gel. The process increases the total pore volume. After being heated above 200°C, the concrete probably contains no liquid water. Increasing the temperature above 600°C, the disintegration of the binder phase occurs as well as the degradation of the entire portlandite into the calcium oxide and water. This breakup is accompanied by a change in molar volume thus creating free space around the former crystals portlandite. At temperatures above 1000 ° C, the degradation of the binder phase and also the decomposition of calcium carbonate to calcium oxide and carbon dioxide become even more evident. Thermal properties of standard and lightweight concrete are slightly different. Lightweight concrete has better properties and the elements made of it get heated slower and are subject to less thermal expansion. The moisture content in the concrete should be considered the same as the equilibrium content and should not exceed 4% of weight of the concrete. Consideration of concrete moisture may be indirectly incorporated in calculation via the change in the specific heat in the temperature range 100 - 200 ° C.

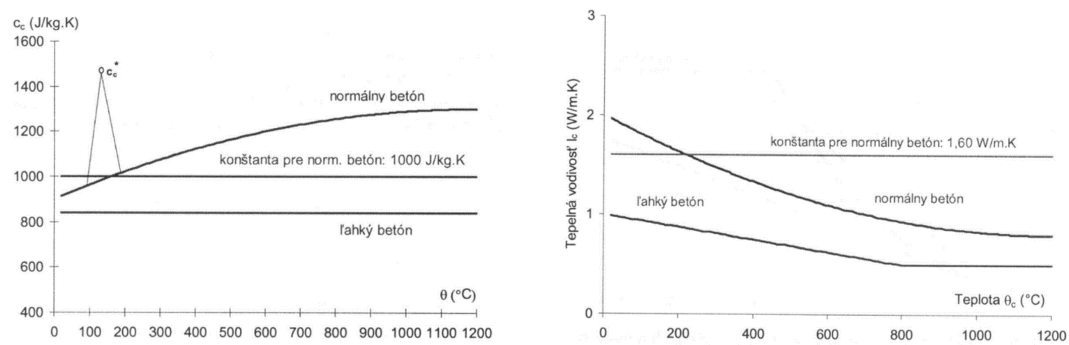

Fig. 1: Thermal properties of concrete

2.2 Thermal properties of steel

Properties of structural steel under fire are provided by standards EC2, EC3 and EC4 in its section 1.2. The thermal properties involve the strain (linear expansion), specific heat capacity, and thermal conductivity. In the calculations may be considered with simplifications but with average values.

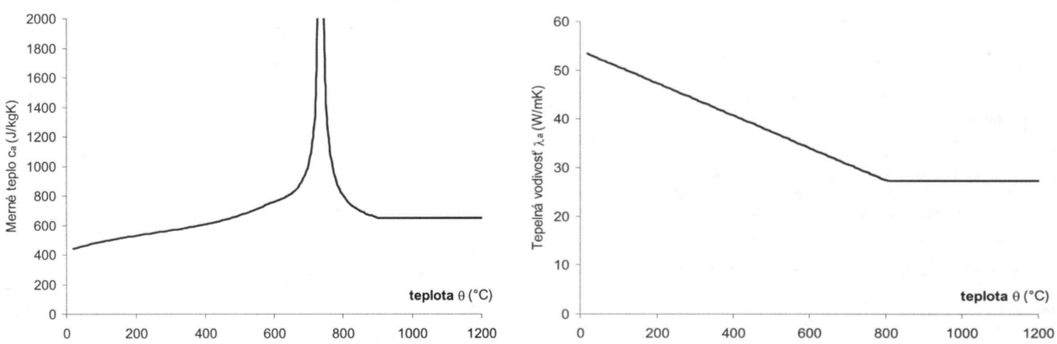

Fig. 2: Thermal properties of steel

3 CONCRETE COMPOSITE CROSS-SECTION

A composite column in with the octagon-shape of cross-section , with a diameter of 270 mm and with the design plastic resistance of 6000 kN was chosen to obtain a representation of the course of temperatures in the cross-section composite columns, depending on the temperature boundary conditions and material characteristics. Quality of considered concrete is C30/37 with an area 2300 cm^2. Internal steel crisis has an area of 59 cm^2, the wall thickness is 5 mm and flange is 7 mm wide. The given geometry formed the basis for 9 models on which sectional maximum and minimum cross-sectional temperature was set, as well as the difference of these two values at a time up to 180 minutes.

Tab.1: Properties of models

MODEL		CONCRETE MOISTURE	BOUNDARY CONDITIONS	SPECIFIC HEAT J.kg-1.C-1		DENSITY kg.m-3		THERMAL CONDUCTIVITY W.m-1.C-1	
				CONCRETE	STEEL	CONCRETE	STEEL	CONCRETE	STEEL
MODEL 1	NONLIN.	0,0	ISO	900 ~ 1100	437 ~ 2273	2300 ~ 2024	7850	1,333 ~ 0,594	53,33 ~ 27,3
MODEL 2	NONLIN.	1,5	ISO	900 ~ 1100 c.peak=1470	438 ~ 2273	2300 ~ 2024	7850	1,333 ~ 0,595	53,33 ~ 27,3
MODEL 3	NONLIN.	3,0	ISO	900 ~ 1100 c.peak=2020	439 ~ 2273	2300 ~ 2024	7850	1,333 ~ 0,596	53,33 ~ 27,3
MODEL 4	CONS.	0,0	ISO	900	437	2300	7850	1,11	45
MODEL 5	CONS.	0,0	ISO	900	600	2300	7850	1,11	45
MODEL 6	NONLIN.	0,0	R=0,7 C=25	900 ~ 1100 c.peak=1470	437 ~ 2273	2300 ~ 2024	7850	1,333 ~ 0,595	53,33 ~ 27,3
MODEL 7	NONLIN.	0,0	R=0,8 C=25	900 ~ 1100 c.peak=2020	438 ~ 2273	2300 ~ 2024	7850	1,333 ~ 0,596	53,33 ~ 27,3
MODEL 8	CONS.	0,0	R=0,7 C=25	900	600	2300	7850	1,11	45
MODEL 9	CONS.	0,0	R=0,8 C=25	900	600	2300	7850	1,11	45

3.1 FEM models

Problems of the spread of heat in a concrete composite cross-section was solved in ANSYS Workbench. Despite the fact that this problem is only a problem of two-dimensional heat transfer, 3D elements SOLID90 were used for easier modeling and they had a thickness of 100 mm. Boundary conditions were then assigned to the side areas with the 100 mm edge. SOLID90 is a three dimensional element with 20 nodes in a shape of cube, tetrahedron, pyramid or prism and it is suitable for thermal analysis.

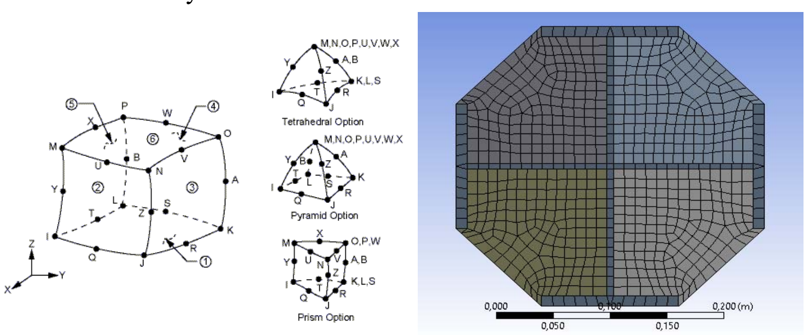

Fig. 3: FEM model in ANSYS Workbench

3.2 Material properties and boundary conditions

Overall 9 models were created having the same geometry but different boundary conditions and material properties. The standard temperature curve ISO 834 was applied as the temperature load in all models. The difference between models is, that in the first five models the radiation or convection were not considered. Temperature curve represents the temperature of the structure. In other 4 models it was considered also with a convection with a value of 25 $Wm^{-2}K^{-1}$ and radiation with a value of 0.7 and 0.8. Models 1,2,3,6 and 7 had a specified value of non-linear thermal properties of material, changing with respect to the temperature. The detailed characteristics of each model are given in Table 1 [4].

4 RESULTS OF ANALYSIS

The results are divided into two separate groups - in terms of material properties, and in terms of choice of boundary conditions. Detailed results in time of 5-180 minutes are shown in Tables 2 and 3. In the first group, i.e., the effects of properties of the specific heat capacity and thermal conductivity coefficient of nonlinear and constant values it can be stated that the impact of moisture concrete with 0, 1.5 and 3, which is represented by the peak values of specific heat capacity c.peak is most significant in time of 30 minutes with the temperature difference between models 1,2,3, up to 50°C. The profile is heated much faster when linear characteristics are used. This rate is most obvious, of course, especially at the end of the analysis in the time of 180 minutes, when the temperature difference between coolest and hottest parts in models 4 and 5 is up to 95 degrees Celsius. In time of 180 minutes the difference in models 1,2,3 is up to 250 degrees.

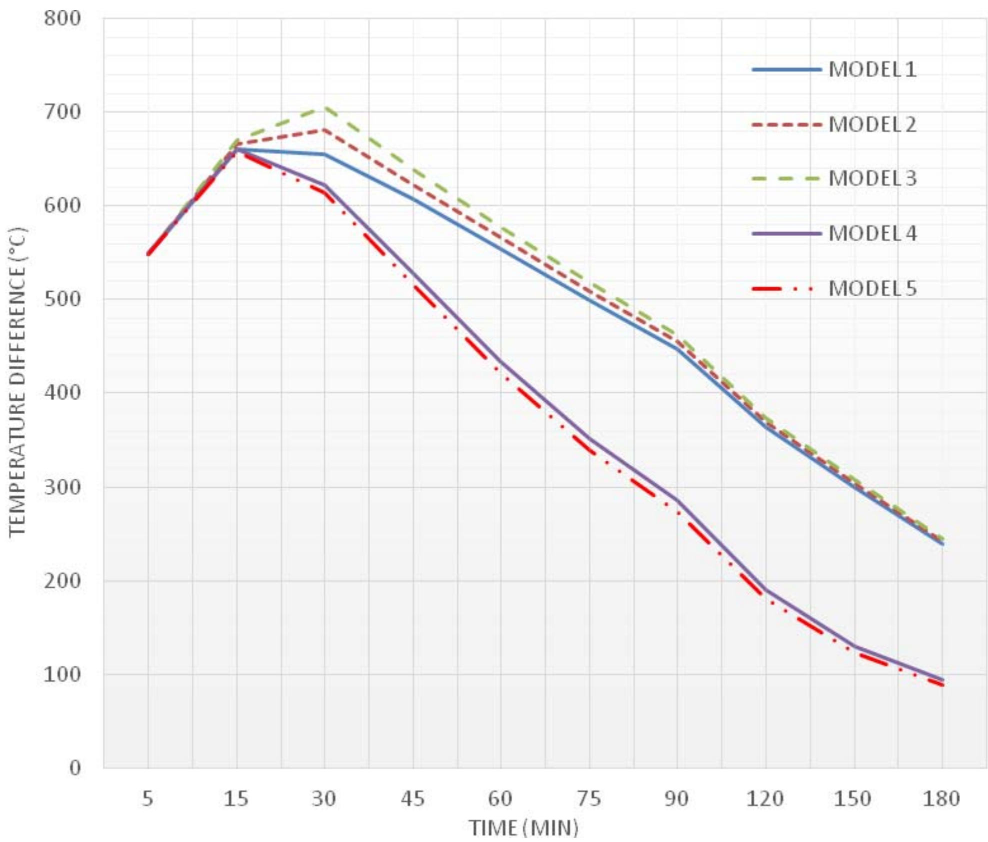

Fig. 4: The graph of maximal temperature difference for models 1 to 5, depending on the material characteristics

The effect of boundary conditions was studied in the second group. Boundary conditions for each model are described in detail in Table 1. In this context it may be stated that the boundary conditions defined in the Eurocode, i.e. model 6,7,8 and 9 reflect more closely the heating profile, especially in the early stages of the fire when the maximum values as well as the maximum and minimum difference are significantly lower than in models 1 and 4. The results are summarized in Table 3.

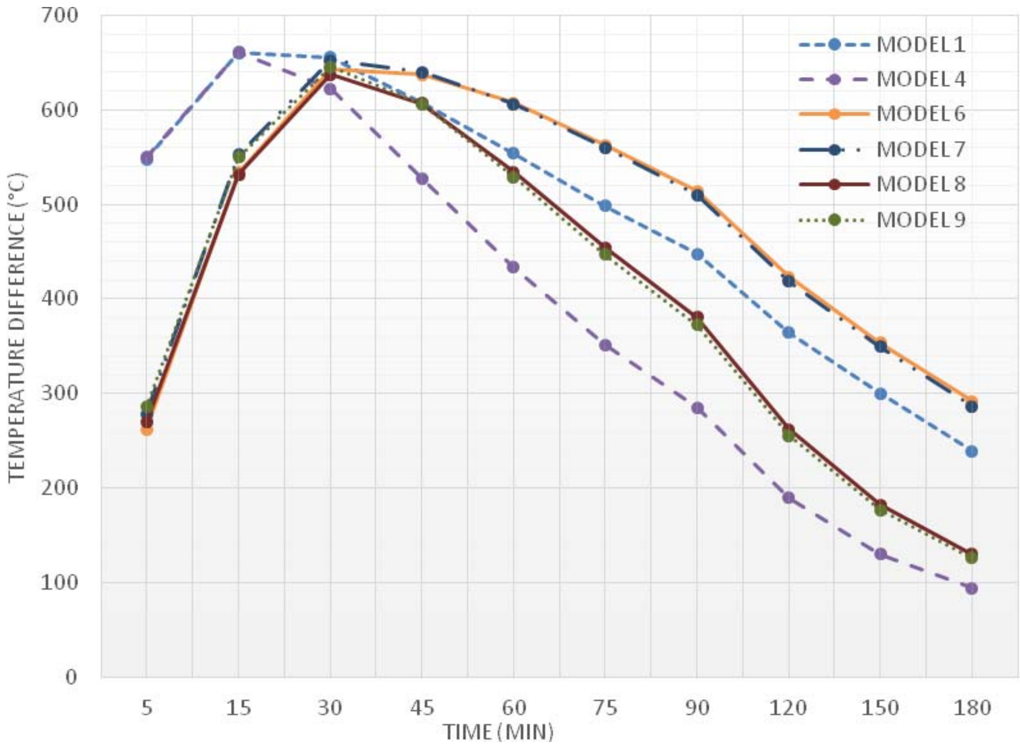

Fig.5: The graph of maximal temperature difference for models 1 to 9, depending on the boundary conditions

Tab. 2: The results in the first group, i.e. dependence on the values of material characteristics in Models 1 to 5.

TIME min	TEPERATURE IN °C														
	MODEL 1			MODEL 2			MODEL 3			MODEL 4			MODEL 5		
	MIN	MAX	Δ	MIN	MAX	Δ	MIN	MAX	Δ	MIN	MAX	Δ	MIN	MAX	Δ
5	28,32	576,4	548,1	27,75	576,4	548,7	27,37	576,4	549	26,76	576,4	549,6	27,36	576,4	549
15	78,14	738,6	660,4	71,97	738,6	666,6	68,34	738,6	670,2	77,53	738,6	661	81,07	738,6	657,5
30	186,6	841,8	655,2	161	841,8	680,8	136,4	841,8	705,5	219,2	841,8	622,6	227,7	841,8	614,1
45	294,1	901,4	607,3	278,7	901,4	622,7	262,4	901,4	639	374,1	901,4	527,4	385,6	901,4	515,8
60	391,2	945,3	554,2	379,6	945,3	565,8	367,9	945,3	577,4	511,8	945,3	433,6	524,1	945,3	421,2
75	479,7	978,4	498,7	470,2	978,4	508,2	460,8	978,4	517,6	626,8	978,4	351,6	638,9	978,4	339,5
90	558,4	1006	447,6	550,8	1006	455,2	543,2	1006	462,8	720,7	1006	285,3	732,1	1006	273,9
120	684,9	1049	364,1	680	1049	369	675,2	1049	373,8	859,2	1049	189,8	868,4	1049	180,6
150	782,2	1082	299,8	778,4	1082	303,6	774,7	1082	307,3	951,7	1082	130,3	958,7	1082	123,3
180	870,8	1110	239,2	868	1110	242	865,3	1110	244,7	1016	1110	94,2	1021	1110	89

Tab. 3: The results in the second group, i.e. dependence on boundary conditions in Models 1 to 9

TIME min	TEPERATURE IN °C																	
	NONLINEAR MAT.PROP									LINEAR.MAT.PROP								
	MODEL 1			MODEL 6			MODEL 7			MODEL 4			MODEL 8			MODEL 9		
O.P.	TEMP			R=0,7 K=25			R=0,8 K=25			TEMP			R=0,7 K=25			R=0,8 K=25		
	MIN	MAX	Δ	MIN	MAX	Δ	MIN	MAX	Δ	MIN	MAX	Δ	MIN	MAX	Δ	MIN	MAX	Δ
5	28	576	548	23	285	262	23	302	279	27	576	550	22	292	270	22	308	286
15	78	739	660	47	581	534	48	601	553	78	739	661	40	572	532	42	591	550
30	187	842	655	125	768	643	129	781	652	219	842	623	121	758	637	127	772	645
45	294	901	607	219	856	637	224	864	640	374	901	527	245	851	606	254	860	606
60	391	945	554	310	918	607	317	923	606	512	945	434	378	912	534	389	918	529
75	480	978	499	396	959	563	404	963	560	627	978	352	501	955	454	513	959	447
90	558	1006	448	478	992	514	485	995	510	721	1006	285	608	989	380	619	992	372
120	685	1049	364	617	1041	423	624	1043	418	859	1049	190	776	1039	262	785	1041	255
150	782	1082	300	723	1077	354	728	1078	350	952	1082	130	894	1076	182	900	1077	177
180	871	1110	239	814	1106	292	820	1107	287	1016	1110	94	976	1106	130	980	1106	126

6 CONCLUSIONS

Model 7 is a model defined in Eurocode as suitable model for thermal analysis of an element in the assessment of the fire resistance. It is loaded according to the standard temperature curve ISO 834, the value of radiation coefficient of 0.7 and heat transfer number 25 $Wm^{-2}K^{-1}$ have been included into boundary conditions. For subsequent stress analysis this model should be fundamental, especially considering the requirements for increased fire resistance. Strain of the element is most influenced by the fact whether the engineer considers in his work with constant or non-linear temperature material characteristics. Heating of the modeled element is greatly affected by the engineer choice, which is the most obvious in the maximum time value of 180 minutes.

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